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INTERFACE OF MATERIALS AND STRUCTURES ON AIRFRAMES

PART 2

OUTLINE OF DECISION PROCESS IN STRUCTURAL DESIGN

by

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ABSTRACT:

The decision process in structural design becomes increasingly important with the introduction of new materials. Starting from a consideration of present problems in structural design, an outline is developed for the decision process with particular emphasis on interaction between materials, structures, and design. This outline, however, still lacks the details which are required for an analytical model of the decision process. These missing details are identified and a practical approach toward their solution is shown.

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This report forms the second part of an investigation under the title Interface of Materials and Structures on Airframes. It is sponsored by the Naval Air Systems Command under the cognizance of the Structures Administrator.

The investigation has been conducted at the Naval Postgraduate School, Monterey, California and included a good many visits with aerospace companies and government agencies. As during the first part of the investigation, the willingness of all individuals who were contacted -- too many to be listed here -- to discuss problems in their fields, to give generously of their time and experience, and to extend a spirit of full cooperation, deserves the very highest appreciation.

1. INTRODUCTION

1.1 Basic Considerations

Structural design of aircraft consists of a long chain of decisions. Among them, the basic selection of material and design concept is of fundamental importance. It affects all further details of structural design and the decision process which leads to this basic selection should be clearly visible and traceable. This, however, is not the case and the underlying reasons present a problem of many aspects.

First, there is the uncompleted process of transition from an era when decisions were based on experience, judgment, and intuition of the structural designer to a world of specialization, automation and system engineering. A methodology for making decisions about the structural design of high-performance aircraft has not yet been developed.

Second, interaction between materials and structures, which has always been at the root of structural design, has assumed a new significance in recent years. Many everyday surprises bear witness to the fact that minor changes in materials processing or in environmental or operational conditions can have major consequences for materials characteristics and may result in greatly reduced airworthiness of the structure. Problems in the fields of fatigue, fracture toughness and stress corrosion are being encountered on materials which had been considered fully developed, tested, and evaluated.

Third, these difficulties on conventional materials are a poor omen for the introduction of new materials. Much uncertainty exists about puzzling surprises which have to be anticipated until considerable experience has been accumulated on components built of new materials. As a consequence, hundreds of millions of dollars have been spent on the development of new materials with promising properties. Yet the return for this investment is highly unsatisfactory. New materials are introduced into aerospace structures at an agonizingly slow rate, and a wide gap exists between research and development of a new material and its structural application.

Among these problem areas, the slow rate of introducing new materials has been the subject of particular concern. No clear conclusions are yet available but there are many contributing factors: lack of providing incentives for the application of new materials, lack of appreciation for risk and time involved, lack of definition for materials capabilities, requirements, and evaluation techniques, lack of flight performance data, doubts about cost effectiveness, etc. It appears that a common denominator for many of these aspects can be found in the procedure of selecting the material and the design concept for a structure. The corresponding design process is the subject of the present investigation.

The design process is based on the skill of the engineer to combine his experience of the past with his vision of the future. This intuitive aspect has to be combined with a rigorous analytical discipline into a systematic procedure. The need for analyzing an enormous number of conditions has intensified a general reliance on computerization, and computer programs exist for many partial aspects of structural design. However, no program can easily be expected for the complexities of interaction between materials and structures, and there is some danger that we may find ourselves in a position where details are being solved at the expense of overall judgment.

In order to see this problem in its proper perspective, it may be visualized as just another aspect of the most pervasive task which has to be faced in our technological society: to find the balance between rapid technological advances and much slower general developments. With respect to materials and structures, the rapid technical progress in the fields of materials development and structural analytical methods has outpaced our capacity to investigate all the aspects of a complex system and to find an optimum solution.

The basic problem consists of clarifying the design process. This may ultimately lead toward a well-defined analytical model for the decision process in structural design which will enable the computer to produce "the" right design for a given set of conditions. Perish the thought! However, there is some reasonable hope that, before this point is reached, man-computer relationship will have achieved a state of intimate flexibility which will avoid rigid and righteous answers but will rather offer well-reasoned alternatives.

The introduction of new materials into aircraft structures and a solution for the problems of interaction between materials and structures will depend largely on developments in this field.

1.2 Scope and Purpose

The present investigation is based on the premise that clarification of the design process in general and of the decision-making process in particular is a problem of fundamental importance. Such clarification has to include fields which have been peripheral to the main line of engineering interest and which are not well defined at all. As a consequence, this report is written on a verbal-analytical level which may be somewhat disappointing to the engineer who lives in a neat world of mathematical formulations and numerical values. At the same time, this lack of mathematical precision emphasizes how primitive the state of the art is with respect to many aspects of the design process.

The purpose of this report is:

a. to apply basic design considerations to the decision process in structural design;

b. to develop an outline for the decision process which can serve as the framework for future analytical models and as a basis for further discussion;

c. to focus attention on some problems which have not been properly appreciated by the engineering community and which have to be solved before an analytical model for the decision process can be developed;

d. to arrive at practical conclusions and a corresponding recommendation.

1.3 Summary of Previous Report

The previously published part 1 of this investigation (Ref. 1) had the subtitle Basic Design Considerations. Its basic purpose was to provide a systematic survey of fundamental problems with respect to the interface of materials and structures on airframes. An effort was made to show the three fields of materials, structures, and design in proper proportion and to define basic problems in each respective field.

In the field of materials, a wide gap has developed between materials R & D and actual application of new materials to aircraft components. Systematic development is required in the fields of materials application, materials evaluation techniques, and data information systems.

In the field of design, much systematic work is required with respect to trade-off factors. Qualitative values have to be expressed in quantitative terms and have to be incorporated into the technical decision process.

In the field of structures, the role of judgment and experience during the early design phases is particularly important as a safeguard against the type of unsuspected failures which are not covered even by sophisticated computer routine.

The conclusions resulted in the definition of three major problem areas:

a. the gap between the results obtained from materials R & D and data which are required for applying new materials to aircraft production;

b. the need for expressing qualitative design considerations in terms of quantitative values and for making systematic use of experience;

c. the fundamental transitions taking place in aircraft design which are related to the field of interface between materials and structures.

Steps toward solution of these problems were recommended in some detail.

2. PRESENT PROBLEMS IN STRUCTURAL DESIGN

2.1 State of the Art

Structural design depends on the state of the art in the fields of materials and structures. These two fields which are based on very different backgrounds have to merge during the process of structural design and the objective is to find a systematic procedure for this merger, taking into account all the inherent complexities. For a practical approach toward clarifying the structural design process, it may be appropriate to start with posing two basic questions: where do we stand and where are we going?

Important aspects of the first question regarding the present situation are considered in recent publications. Ref. 2 is concerned with the frontiers in aircraft structural design, points out the basic dilemma of the structural designer between the difficulties of sound technical judgment early in the design process and the temptation of overoptimism, and discusses promising areas of structural technology. Ref. 3 considers the influence of new materials on aircraft design and points out the dilemma of having many promising materials available which are being withheld for numerous reasons. Ref. 4 gives a survey of fatigue and fracture mechanics -- a field which has been particularly troublesome in aircraft design and where fracture mechanics analysis procedures are not yet adequate for complex structural and loading conditions. Ref. 5 contains the papers of a symposium on engineering practice to avoid stress corrosion cracking -- another field which has caused much grief in recent years.

The second question regarding the future course of developments is not as well documented. However, it takes no gift of prophecy to recognize that we stand at the threshold of a new era in structural design as many new materials become available for manufacturing and as computerization increases rapidly in structural analysis. This calls for a basic reappraisal of present methods, techniques, and attitudes, for an honest readiness to adopt the new, but also for a genuine awareness of the many possible pitfalls. A review of some of the present problems will serve as a reminder of the realities of life.

2.2 Lessons from Recent Experience

Structural design has achieved a good record of structural safety, particularly for transport aircraft. Yet much of the experience was gained the hard way and an excessive amount of maintenance and repair has been required. Fatigue and stress corrosion alone are estimated to have cost several hundred million dollars in necessary repair of aircraft during the past decade. The lessons learned from this experience must be evaluated for the design process and for future application of new materials.

Thanks to fail-safe philosophy, in most cases the damage was limited to the field of economics. The main culprits during the recent past have been cracks due to fatigue and stress corrosion. They came as a particular shock because they affected parts which had been considered analyzed and tested satisfactorily and they demonstrated the ever-present danger of disturbing surprises.

The seriousness of the situation can be realized from Ref. 6 which describes and discusses difficulties encountered on a recent military aircraft with high-strength steel. Specific causes for the difficulties are pinpointed in the fields of stress concentration, manufacturing techniques, and inspection methods and are correlated with theoretical considerations of fracture mechanics. Other similar difficulties show somewhat different causes but they are always typical of the problems of interaction between materials and structures.

Examples of fatigue cracking show clearly the intricate interaction between load spectrum in the field of component design data; fracture toughness, fabrication, processing, and maintenance in the field of materials; stress concentration and design stress level in the field of structures; and meticulous attention to every detail in the field of design.

Examples of stress corrosion cracking show the same kind of interaction, with special emphasis on environmental conditions, sensitivities to alloy composition and heat treatment, residual surface stress, grain direction, and many others.

Neither fatigue nor stress corrosion were new problems when they descended upon the aircraft industry with unsuspected vehemence. A great amount of additional research, both theoretical and experimental, has been going on since but there is still only limited theoretical understanding which has to be supplemented by tests and practical experience. Tests are meaningful only when they are conducted under real-life conditions although the influence of some of the parameters is often poorly understood. The importance of component testing of considerable complexity, going far beyond the traditional static and fatigue tests, becomes apparent.

Investigation of typical examples for fatigue and stress corrosion cracking always indicates some cause which can be well identified from hindsight. It usually is the result of interaction between various contributing influences. It could have been prevented in structural design because this is the place where all basic responsibilities are centered, including concern about availability of manufacturing techniques as well as inspection methods.

Yet typical examples are not caused by incompetence in structural design. An amazing amount of knowledge and experience has been accumulated among responsible engineers in all major aircraft companies. The basic problem consists of the multitude of interactions and the difficulty of investigating all aspects as the state of the art is pushed forward another step. It boils down to a question of organization for the design process.

The preceding considerations are concerned with typical difficulties which have occurred during the past decade. Materials which had been developed systematically and tested extensively over a period of many years still provided unfortunate surprises. A new situation is developing as many new materials will be available in the near future. Each of these requires elaborate testing. Some may be non-homogeneous, anisotropic, brittle, etc. and it must be anticipated that new difficulties will arise which cannot be foreseen yet. This is the clear lesson to be learned from recent experience.

2.3 Materials

With respect to structural application of materials, a considerable gap has developed between well-established materials research and ill-defined materials application. This gap will have to be bridged by "materials engineering". The term implies a responsibility which is not directed toward materials research and development but toward component design, manufacturing, processing, and maintenance. Materials engineering requires a strong theoretical background in structural engineering as well as in material science and much practical experience in order to provide the important link between materials R & D and structural design.

These considerations bear directly on the role of materials in structural design. Introduction of new materials results in increased importance of materials engineering -- similar to the situation which has developed in spacecraft design. The implication that materials have a basic significance which is equivalent to either structures or design presents a departure from the traditional approach in aircraft design. The various aspects of materials have frequently been distributed among the manufacturing group for fabricability, the structures group for mechanical properties, and the design group for general considerations. With a large number of new materials under consideration, such a decentralized approach will not be feasible any more. A materials group will have to take responsibility for all aspects of materials just as a structures group is responsible for all aspects of airworthiness. Otherwise it would never be possible to make a valid comparison between various materials and to provide for a systematic approach to material selection. These considerations are incorporated in Section 3.

A second aspect of materials application is the need for clearly defined evaluation techniques. Much has to be done in this field. It deserves special emphasis that the lack of this type of criteria for design application has been mentioned as a subject of major concern by several committees of NASA and of the National Materials Advisory Board (Ref. 7, 8 and 9). These voices have been clear and explicit but no results have been noticeable yet and there remains a glaring gap which affects the design process.

A third aspect of materials application is the need to identify critical material parameters for a given application. This requires clearly defined component design data, including the full spectrum of operational and environmental conditions. Their importance will be discussed in Section 4.5.

A fourth aspect of materials application refers to the very basic problem of acquisition and evaluation of data on materials characteristics at the proper environmental and operational conditions. The sheer quantity of necessary data for high-performance aircraft is overwhelming. It must be realized that previous problems will be greatly multiplied in the near future. As a consequence, a special effort is required regarding

a. collection, interpretation, storage, and dissemination of the vast amount of test data which are being published;

b. publication of data generated by government contracts;

c. exchange of proprietary data within the industry on a give-and-take basis;

d. coordination of development work to avoid time-consuming gaps and money-wasting overlaps.

A further aspect of materials application is the need for flight evaluation. A practical approach consists of defining typical components which can be installed on available aircraft and which may be made of different materials for evaluation and comparison. This has been done on several recent development programs.

All these considerations regarding materials application become fundamentally important with the introduction of new materials. Additional conclusions and recommendations regarding the introduction of new materials are given in Ref. 9.

2.4 Structures

Much progress has been made in the field of structures with respect to overall analysis. Computerization has progressed toward composite computer programs for combining detail programs of structural analysis into an overall analysis of large structures. Programs are mostly based on the finite element method and can be applied to an entire wing or fuselage, including discontinuities. The results are in form of stress, displacements, and frequencies. FORMAT and ASKA became available in the late 1960's, NASTRAN in 1970 -- naming only a few out of many comprehensive computer programs. Systematic development work along these lines requires a continuous effort but the basic problems seem to be under control and technical competence is approaching a level where overall analysis of strength and stiffness can be treated as an analytical routine.

On the other hand, however, there is much to be done with respect to detailed analysis. The examples cited in Section 2.2 have a sobering effect by showing the complexities of interaction between materials and structures. There is still much uncertainty about details of fracture mechanics and about the influence of processing techniques, manufacturing practices, and minute engineering details. Minor modifications may result in major difficulties. Environmental conditions have to be fully considered. This is the crucial region of the interface problem between materials and structures. It has not yet been solved for well-established materials and causes much apprehension regarding new materials.

Regarding the interaction between materials and structures, progress in the theoretical field can be expected to be slow. Evaluation of test data remains a major source of information and requires close cooperation between materials and structures. Again the examples cited in Section 2.2 may be used to indicate the need for proper planning of tests which includes timing in order to have the necessary information at the proper time and a test setup which yields as much information as possible and can be correlated with analytical interpretation of results. The cost of testing can often be reduced by more comprehensive analysis of test results.

Experimental data have to be combined with experience for structural analysis. Both will be in short supply and have to be husbanded when it comes to the introduction of new materials. Specific suggestions are made in Ref. 1 with respect to systematic use of experience, exchange of information, and case studies of problems which have been encountered. A stepwise approach toward a general solution may be most appropriate but it is important to recognize the magnitude of the problem as many new materials are introduced.

Computer programs are also available for detail analysis. In this connection it is particularly important to recognize the full potential of the computer without losing sight of its constraints. The type of interaction which is taking place between materials and structures cannot easily be programmed in the foreseeable future. The computer will remain a tool and will not replace the judgment of the engineer. Of course, it will free the engineer's mind for exercising his judgment.

From the general viewpoint of airworthiness, the main problem consists of providing a safeguard against unsuspected failures. Yet, in general, no assurance can readily be given that all potentially hazardous details have been fully analyzed. The only safeguards against disastrous surprises in the field of structures are everlasting vigilance and good judgment based on extensive experience -- a state of mind to probe into every aspect of a new problem, to investigate it analytically and experimentally, to consider the risk in loads, in allowables, in detail stresses, and in fatigue. A methodical approach will require more than purely analytical methods. They have to be combined with an inspiring exchange of ideas among adjacent disciplines and with a systematic procedure. This means a challenging situation to establish a clear man-computer relationship in the design process.

3. PRESENT ORGANIZATION OF STRUCTURAL DESIGN

3.1 Design Philosophy

Our present design philosophy is the outcome of a development which became visible in the 1950's and was intensified throughout the 1960's. Increasing complexity of high-performance aircraft resulted in increasing demand for teamwork, increasing need for analytical methods, increasing amounts of data to be evaluated, increasing use of computers, and ever-increasing cost. Both cost and time considerations have eliminated the prototype which previously provided a convenient method of developing and evaluating new ideas. Instead of this, a new aircraft is expected to be basically ready for production because any later modifications are prohibitively expensive. The responsibilities imposed by a multi-billion dollar project are tremendous. Most of these responsibilities rest on "advanced design" as the originator of the basic decisions which make or break an aircraft project.

The importance of advanced design is recognized throughout the aircraft industry. Advanced design groups are staffed with highly talented engineers of long and broad experience who have at their disposal the advice of specialists within the company. Advanced design begins with the early stages of parametric performance studies which result in the sizing of the aircraft, and it finally leads to a structural design which provides the airframe data required for submitting a detailed proposal. A large number of iterative steps is necessary during this design procedure. The final outcome of advanced design is expected to be sufficiently comprehensive so that further detail design requires no basic decisions or modifications. All the important decisions regarding interface between materials and structures are made in advanced design.

3.2 Design Procedure

Design procedures grow organically in each aircraft company. They depend on individual conditions of available talent, manpower, and experience. There are, however, some basic aspects which are of consequence with respect to the interaction between materials and structures.

For the present considerations, the design procedure during the phase of parametric studies offers no special interest because the parameters are based on a high level of abstraction. Real-life complexities enter only when it comes to the actuality of structural design. Only this phase will be considered here in more detail because it covers the basic decisions regarding choice of material and structural configuration and is, therefore, of fundamental importance for the problems of interface between materials and structures.

Some basic characteristics which are typical of the present situation in the aircraft industry can be observed:

a. The term structural design contains the duality of structure and design which has to be resolved into the entity of structural design. Structural aspects imply analytical methods for calculating strength and stiffness; design aspects imply the overall responsibilities of system design as well as the details of nuts, bolts, and dimensions. A synthesis of these different aspects has been well accomplished in advanced design groups but it is significant to realize that the structural designer frequently thinks of himself either as a structural engineer or as a design engineer, depending on his personal background and on company organization. The essential point is, of course, that in either case he has absorbed so much of the other viewpoint that he thinks and acts in accordance with the integrated viewpoint of the structural designer.

b. With respect to company organization, there are two schools of thought: advanced design is either closely linked with structural mechanics in order to emphasize the importance of analytical methods for minimum weight or it is closely linked with system design in order to emphasize the importance of overall design considerations. This is the same duality on an organizational level as encountered on an individual level in the preceding paragraph. Again the essential point is that organizational setups do not stifle the spirit of advanced design which requires free roaming over all aspects of the overall system as well as disciplined analytical methods. It seems that this has been basically accomplished throughout the aircraft industry and that organizational variations are not of any major consequence at present.

c. Among the many aspects which the structural designer has to coordinate, closest cooperation with materials engineering has assumed prime importance. This is generally recognized and much progress has been made in recent years but continuous improvement is being sought.

d. Another major aspect incorporated in advanced design is cost effectiveness. This includes cost of development, fabrication, and total life cycle of the aircraft. Value engineering is responsible for evaluating any design concepts from this viewpoint.

Flow charts to identify the design process in the aircraft industry are being used as deemed practical but there is no overall pattern recognizable. Such charts range from sketchy outlines to long walls of sticker boards with intricate details. The development of comprehensive computer programs has stimulated the need for these models for flow of information.

They are directed toward integrating independent computer programs as modules of an overall design process. Within this process, however, the problems of interaction between materials and structures and of design optimization have not been given full attention as yet.

Up to this point is has been possible to describe the common basic aspects of advanced design groups. From here on, when it comes to the working details of structural design regarding systematic approach, methods, sequences, consideration of environmental and operational conditions, and design decision process, no common denominator is readily recognizable any more. Advanced design groups of different companies use different approaches which may or may not be well-defined and which usually are empirical. This is particularly true regarding interaction between materials and structures as well as design optimization.

These approaches are based on analytical considerations which are mostly the same everywhere but which are combined with different individual experience. In addition to analytical methods with clearly defined quantitative data, qualitative values are included. However, contrary to the rigorous quantitative data, qualitative values are usually treated in a somewhat informal way because there is no agreement on any methodical procedure. In spite of this, final results have generally been in good agreement irrespective of the individual approach. This indicates an equally high degree of expertise and experience found in different advanced design groups.

3.3 Trends in Structural Design

The growing complexity of problems in advanced design results in increasing computerization. Analytical models have been developed for the sizing of various structural elements under simple conditions. Further efforts are directed toward taking into account a large number of environmental conditions, load requirements, manufacturing considerations and potential modes of failure and toward combining them into a general analytical model for sizing of larger structural components under real-life conditions.

Analytical models, of course, require a clear methodology. This exists in the field of overall analysis for strength and stiffness of structural components. It appears, however, that not much of a systematic effort has been made to develop such a methodology for other aspects of the design process. Interaction between materials and structures as well as design optimization with corresponding trade-off considerations belong in this category of inertness although they are of basic importance for structural design.

4. GENERAL ASPECTS OF STRUCTURAL DESIGN

4.1 Definitions

Many of the terms which refer to the design process are subject to different connotations. It is necessary, therefore, to define the interpretations which will be used:

Aircraft design refers to the overall design including parametric studies, performance, aerodynamic characteristics, propulsion, basic loads, structural design, etc.

Structural design refers to all aspects of the load-transmitting structure, including selection of material and structural configuration, design details, structural analysis, substantiation of airworthiness, weight, cost, fabricability, and maintainability. For high-performance aircraft, structural design has to be based on well-defined operational and environmental conditions which generally vary from one structural component to another, frequently even within one component.

Advanced design refers to that part of structural design which includes selection of material and structural configuration as well as all basic decisions.

Detail design refers to the final part of structural design where the decisions made in advanced design are translated into final working details and into full substantiation of airworthiness.

Decision process in structural design refers to the procedure of making design decisions. This procedure depends on the type of structural component.

Operational conditions refer to external and internal loads with the resulting stresses and deformations under all loading conditions.

Environmental conditions refer to ambient conditions which may be either natural (atmosphere) or artificial (e.g. fuel) and will include magnitude and duration of ambient temperature, corrosive influences, radiation, etc.

Component design data are derived from the operational and environmental conditions which have been determined for the aircraft. These data define the specific conditions on which the design of each component has to be based.

Materials responsibilities include establishment of data on materials properties, processing, fabricability, inspectability, and maintainability as well as materials testing, evaluation, application, maintenance, and follow-up procedures, i.e., all aspects of materials behavior from cradle to grave.

Structures responsibilities include static and dynamic analysis for strength and stiffness as well as testing of structural components, i.e., all aspects of airworthiness at minimum structural weight.

Design responsibilities include the traditional field of detail design as well as overall design concept and the various aspects of optimum design (cost, risk, time schedule, and trade-off considerations), i.e., all aspects of coordination and optimization.

In accordance with these definitions, design forms only a specific part of the much wider considerations of structural design. On the other hand, structural design is only a part of the overall considerations of aircraft design.

It is also obvious that there will always be some border regions between the fields of materials, structures, and design which require clear assignment of responsibility.

4.2 Fundamental Considerations

The discussion of Section 3 indicates that no generally recognized and clearly defined design process exists which takes into account all the complexities of structural design. It will be necessary, therefore, to begin with some basic considerations.

The structural design process contains four general aspects:

a. A design concept has to be developed, based on clearly defined specifications;

b. The characteristics of available materials and the methods of fabricating and processing them into a structure have to be scrutinized;

c. Analytical methods have to be used for strength, stiffness, flutter, fatigue, fail-safe, and other airworthiness requirements.

d. The structural design has to be optimized with full consideration of all implications.

The structural design process consists of a highly iterative procedure which is based on continuous interaction between these four general aspects. This procedure which in the past has partly taken place within the mind of a single engineer has to be transformed into a methodical approach for a team of engineers.

At present, the structural design process suffers from a considerable one-sidedness. It utilizes sophisticated analytical methods of structural mechanics while materials selection is still handicapped by a lack of test data and a lack of agreement on evaluation techniques, while detail analysis is poorly prepared for the complexities of interaction between materials and structures under varying environmental and operational conditions, and while design optimization and decision-making process -- the most basic aspects of design -- are still in their infancy. These discrepancies affect the design process in many respects. One of the most obvious consequences is availability of well-documented data on structural analysis while there is a scarcity of systematic information on most other aspects of structural design.

A general approach to the structural design process will have to satisfy different viewpoints:

a. The airframe manufacturer needs an approach which gives full assurance that decisions regarding material selection and structural configuration are based on all available information, that airworthiness requirements are met, that potential difficulties are systematically investigated, and that a near-optimum solution is obtained.

b. The procuring agency wants, beyond this, an approach which provides a common basis for evaluating and comparing various proposals and which, in addition to giving quantitative data, identifies assumptions, constraints, anticipated difficulties, and line of thought leading to a particular solution.

c. The materials manufacturer wants an approach which identifies environmental and operational conditions to be met by the material for a specific component.

d. The researcher in the field of optimal structural design will need a solid foundation for applying mathematical programing methods which are in the process of development.

Providing for the full complexities of interaction between materials and structures and of design optimization requires consideration of some organizational aspects of structural design. Any attempt to suggest a

rigid organization chart would obviously be unrealistic, futile, and foolish. However, it should be feasible to develop a general framework which can be modified for individual cases but which demonstrates essential features. This will serve to articulate a process which might otherwise be overshadowed by developments in computerization.

Since no systematic work has been done in this field, there is a great diversity of viewpoints and opinions. Many common aspects appear in different forms. The following considerations, therefore, should not be understood as a new system or a polished end product but rather as a clear basis for discussion in order to identify methods for solving basic problems.

4.3 Principal Steps in Aircraft Design

A simplified model of the aircraft design process is given in Fig. 1. It shows how structural design is the third of three principal steps:

a. Parametric Studies, based on the interrelationship of performance parameters, and resulting in sizing and mission analysis of an aircraft -- a highly iterative process;

b. Basic Loads, based on the aircraft layout which has been chosen from parametric studies, and resulting in definition of design conditions for the aircraft;

c. Structural Design, based on transforming the design conditions and specific requirements for the aircraft into design data for each component, and resulting in advanced design and final analysis, drawings, and specifications for each component. A final feedback is provided in form of data on weight, cost, reliability and anticipated difficulties which are an output of structural design and have to agree with the original input of the design concept.

Similar models may be found in the aircraft industry in many variations. The two fields of parametric studies and basic loads due to operational conditions have been given much attention over many years. As a consequence, well-developed computer programs have become routine procedure in these two fields. Their outcome is available and forms the basis for structural design.

The third field of structural design presents the essential step toward facing all the realities and complexities of an actual structure. Contrary to the widely explored fields of parametric studies and basic loads, the process of structural design still requires much basic clarification.

4.4 Triangle of Structural Design

The definitions given in Section 4.1 for the responsibilities of materials, structures, and design indicate that the purely technical considerations of interaction between materials and structures do not suffice for the purpose of structural design. The wider responsiblities of design regarding optimization and trade-off considerations have to be included as an essential part. This means interaction between materials, structures, and design.

It is also seen that operational and environmental conditions generally vary from one component to another, resulting in different design data and in a different set of problems for each. Fuselage, lifting surfaces, landing gear, engine support, etc. are major design groups. For purposes of structural design, however, a further breakdown is usually necessary and components can be identified which serve the same functional requirements and have similar geometry. A fuselage, for instance, may be broken down into structural components consisting of fuselage shell, fuselage frames, windshield, attachments for concentrated loads, etc.

These considerations show that any discussion of materials application is meaningless unless the design data can be clearly defined for a specific component and closest coordination between materials, structures and design can be accomplished. A general framework for the structural design process, therefore, has to consider component design data, materials, structures, and design. Each of these aspects -- as defined in Section 4.1 -- represents a different viewpoint with respect to purpose, characteristics, and background and each is based on a different discipline of engineering. Yet their full integration throughout the process of structural design is essential.

Fig. 2 is based on the preceding considerations. It is conceived as a triangle where the three corners are formed by the three disciplines of materials, structures, and design and the core consists of component design data -- each as defined in Section 4.1.

This triangular representation emphasizes mutual interdependence and interaction. Structural design must be considered as an entity. Each of the three corners of the triangle is directly connected with the core as well as with the other corners. The basic concept of Fig. 2 will run through all the following considerations and will be discussed in more detail in the following sections.

4.5 Core of the Triangle

The triangle of structural design as shown in Fig. 2 has a core which is

of fundamental importance. It consists of component design data specifying the given design conditions. Full identification of these component design data is, of course, the basis of structural design.

The sources for component design data are shown in Fig. 1 but some amplification is necessary regarding the contributing parts. The main flow of data is supplied from the design conditions for the aircraft. These overall design conditions have to be translated into applicable component loads, e.g., for a fuselage shell into shear, bending and torsion diagrams, or for fuselage frames into loading diagrams. This may be done by computer routines, with additional consideration for operational and environmental conditions for each component, including load spectra, local temperatures, corrosive influences, etc.

Another flow of data is shown in Fig. 1 as determined by specific requirements. These may include requirements for passengers or ordnance, provision for special equipment, processing specifications, etc.

Specific requirements also include dimensions of the component. These are influenced by the sizing of the aircraft as well as by other considerations which may be caused by space limitations. Introduction of such data serves a dual purpose. Firstly, it defines dimensional requirements. Secondly, it provides for basic dimensions with respect to interpretation of design and test data, including structural index, column length, curvature, etc.

Additionally, specific requirements include constraints which may be imposed by management decisions (e.g., cost, time, risk) or by engineering decisions (e.g., manpower, available experience, production facilities, avoidance of critical frequencies, etc.).

Systematic compilation of these data provides for well defined component design data with all specific information on operational and environmental conditions. Loads, service life, fail-safe requirements, as well as thermal, chemical, acoustical, vibrational and nuclear environments will be included. Also included are considerations of rational probability analysis, load alleviation, mode stabilization, and the concept of control-configured vehicle.

It will be noted that the component design data do not contain any statement regarding choice of material or structural configuration. The objective is merely to establish the basis which is required for the structural design of a component.

4.6 Corners of the Triangle

The idea of having materials, structures, and design as the three corners of a triangle is rather obvious in order to put emphasis on the close relationship and mutual interdependence. With the definitions of Section 4.1, a further point becomes quite clear: interaction between materials and structures is on a purely analytical level and only the addition of design introduces the more general aspects of optimization. In the past, analytical considerations of airworthiness were predominant. With the introduction of new materials, however, it also becomes important to find an optimum solution.

The multitude of responsibilities shown in Fig. 2 is too complex and cumbersome for practical use. It can be broken down, however, into distinct phases which may preferably coincide with the different types of structural analysis to be performed. This is done in Fig. 3.

For each phase of Fig. 3 considerations of materials, structures and design are coordinated. For fatigue, for instance, the materials engineer is concerned with fatigue properties, the structures engineer with fatigue analysis, and the design engineer with design details to avoid stress concentration. While the structures engineer may have a computer program for overall analysis, he still has to consult closely and continuously with materials and design engineers regarding all the details of design, processing and manufacturing.

Each triangle represents a level where much consultation and meeting of minds between various disciplines must take place. In addition to this horizontal interaction, there is vertical continuity in the fields of materials, structures, and design. It is particularly pronounced in the case of structures where vertically a composite computer program may link the various phases instantaneously and provide for overall sizing. The horizontal triangle provides for the interaction of various disciplines which is required for design details where a computerized approach to all the intricacies of interaction can hardly be expected in the near future. This results in a challenging situation with respect to man-computer relationship.

It is typical of Fig. 3 that the triangle of structural design has to be applied to many phases. It is also typical that no further details are given because this is a realm which should be left largely to a non-regimented approach. A system can be devised for any phase when much experience is available. On the other hand, it is important to keep an open and alert mind for any possible surprises. This need for flexibility on a technical level should be recognized as a crucial aspect of interaction between materials, structures, and design -- particularly with the introduction of new materials.

4.7 Basic Components

The framework for structural design as shown in Fig. 3 serves just as a general example. Precise details and subsequent differences have to be considered in accordance with the operational and environmental conditions of a given component.

Since many components are basically recurrent for different types of aircraft, it appears to be quite feasible to develop a basic model for the structural design of a specific type of component. A fuselage shell or a lifting surface are typical examples for major components, a canopy or a pressure cylinder for smaller components. Such a component model can follow the pattern of Fig. 3 but will additionally give details for the range of operational and environmental component design data, for applicable material characteristics, and for analytical methods. This results in identification of controlling parameters for a given type of component and is of basic importance for a systematic procedure in structural design. It also identifies the conditions which have to be met by materials for a specific component, as required from the viewpoint of the materials manufacturer (p. 16).

Much basic work along similar lines is contained in Ref. 10 although the effort was directed toward manufacturing technology. It showed, among other things, the feasibility of an industry-wide approach to a problem of basic importance.

4.8 Summary of Preceding Considerations

The structural design process as outlined in Fig. 3 may be summarized as follows:

a. The design problem is defined clearly by component design data (as shown for the core of the triangle in Section 4.5);

b. Responsibilities are assigned in accordance with three fundamental aspects: materials engineers are responsible for materials evaluation and application; structures engineers are responsible for airworthiness at minimum weight; design engineers are responsible for coordinating design concept, detail design, and trade-off considerations for design optimization (as shown for the corners of the triangle in Section 4.6 and further discussed in Section 5);

c. Closest coordination between these fundamental aspects during each design phase is expressed by a triangle of structural design -- representing a nucleus of interacting ideas, responsibilities, and backgrounds which seems to defy any minutely organized system (as discussed in Section 4.6);

d. The design phases are linked together by the responsibilities in the fields of materials, structures, and design where all phases are integral parts of the overall process of structural design (see Section 4.6);

e. Major supporting facilities are also shown in Fig. 3: materials testing as part of materials engineering, and component testing as part of structures engineering;

f. Each of these responsibilities and facilities involves continuity, beginning at the time of the first formulation of the design concept and ending at the time of final design details;

g. This continuity in each field provides for early anticipation of difficulties in order to avoid a bottleneck or fait accompli further downstream. For instance, trade-off considerations and cost happen to be listed toward the bottom of Fig. 3 but early awareness of any developing problems is provided by the monitory process brought about by clearly defined responsibilities. It should also be emphasized that the various phases may take place either consecutively or simultaneously.

This procedure incorporates:

First, computerized techniques of overall analysis for the sizing of structural elements;

Second, full consideration of design details with respect to the interaction of materials and structures;

Third, emphasis on the need for complete data regarding materials at proper environmental conditions, which is particularly important for the introduction of new materials;

Fourth, provision for the role of design engineering which will be discussed in the following Sections 5 and 6.

5. SPECIFIC ASPECTS OF STRUCTURAL DESIGN

5.1 Design

The responsibilities of design are defined in Section 4.1 as design concept, detail design, and design optimization. These three subjects cover a wide field. Design concept requires a creative mind, detail design is based on precise information and formal documentation, and optimization with corresponding trade-offs demands clarification and weighing of all considerations which may influence the design. From the viewpoint of advanced design, trade-off considerations are particularly important. Their discussion, however, will be postponed to Section 6.3.

Originally, the emphasis in design was very much on concepts where creativity, ingenuity, and intuition of the designer played a considerable role. With increasing specialization, much of the designer's work was taken over by structures engineers, materials engineers, system engineers, value engineers, etc. This detracts from the basic responsibility which rests with the designer. His work is creative work, in spite of the need for systematic approach. The apparent contradiction between creativity and systematic approach does not actually exist because the latter is used merely as a tool to deal with the constraints which are imposed by laws of nature and facts of economics.

The specific role of design is discussed eloquently in Ref. 11. Design has to establish new solutions. Yet our engineering education has produced an imbalance between analysis and design very much in favor of analysis. The analyst can make almost any design workable, whatever its quality. This may easily overshadow some intangible qualities like simplicity and elegance of design. Such intangible qualities are closely related to creativity in the design process but little is done to develop this aspect. Increased analytical capabilities are creating an image which implies that in just about any case we can find an answer through mathematical formulation. Good design, however, depends strongly on very personal qualifications.

5.2 Relationship between Materials, Structures, and Design

These last remarks point toward an aspect of the design procedure which deserves some basic consideration. The triangle of structural design implies team work between materials, structures, and design engineers. This, of course, can easily deteriorate into work by committee with all the corresponding compromises and tedious details which may be detrimental to the inspired initiative of a more individualistic approach.

Yet on the other hand, a creative individual -- the aircraft designer of bygone days -- cannot possibly cope with all the complexities of high-performance aircraft without such interaction. We have to find the proper balance between individual and team, render it possible for the individual to unfold his innate gifts and still to restrict his imagination to the realm of reality by coordinated counsel from his peers. The outcome should hopefully be in line with Alexander Pope:

> "Where order in variety we see
> and where, though all things differ,
> all agree".

The triangle of structural design with its three corners of materials, structures, and design provides for a system of checks and balances. Each corner forms an integral part of an entity and pure teamwork between the three corners can be expected to arrive at adequate results. These, however, may be somewhat mediocre because creative guidance is needed for highest achievement.

Originally, such leadership was exerted by the designer without any dispute. More recently, with increasing dominance of analytical methods, the leading role has been shouldered frequently by the structures engineer. In the case of space vehicles with special problems regarding materials, it is sometimes taken over by the materials engineer. Or, in general, it may be assumed by a project engineer.

The fluctuating border lines between structures and design as found within the aircraft industry are particularly significant. The analytical discipline of structural mechanics has frequently overlapped into the field of design with the analyst taking the initiative. This had very obvious reasons. For quite some time the emphasis in engineering education has been on analytical methods as answer to our problems. The consequence is that many of the most promising engineers became analytical specialists and looked at design from an analytical viewpoint, often without realizing the full implications.

Analytical methods have to be used as tools. The best among analytical specialists are quite aware of this and have reached a degree of maturity and accumulated a breadth of experience which represent enormous assets. They have achieved this by growing beyond their field of specialization and recognizing the full meaning of interaction between various disciplines. When engineers have reached this point, they may take responsibility for either structures or design or both. Yet it takes a great amount of experience before the typical analyst is equipped to deal with the full range of design problems.

Among the design problems, trade-off considerations and optimum design -- which will be discussed in Section 6 -- acquire increasing importance with the introduction of new materials. Basic decisions have to be made after full consideration has been given to a large number of parameters. From this viewpoint, airworthiness may become a routine prerequisite, to be expressed as probability of survival, while the important decisions depend on overall design optimization. Whoever takes this responsibility assumes the role of "primus inter pares" -- first among equals. He has the opportunity for creative leadership and has to satisfy the highest demands on judgment and experience.

This role will necessarily be usurped by the best available talent. It represents the essence of design but there has been some difficulty in finding designers to fill this job. This reveals how pitifully the discipline of design has been neglected in engineering education. Only slowly a realization is growing that design requires a solid analytical background combined with a creative drive and a sense for overall perspective and trade-off considerations -- a combination for which the foundation has to be laid in the engineering curriculum before it can be further developed by practical experience.

This kind of consideration implies the need for much flexibility on an organizational level. Figure 2 identifies typical sub-specialties for the fields of materials, structures, and design. However, they may be modified as the occasion demands by shifting responsibilities between the three fields. In spite of the definitions in Section 4.1, particular solutions must depend on innumerable combinations between available talent, working conditions, and organizational environment which vary from case to case and hold the key as to whether individuals can make full use of their capabilities. No attempt must be made to subjugate all these intangibles under one rigid system.

Yet an essential point has to be observed: the responsibilities for each step must be clearly defined and allocated throughout the design process and full interaction must exist between materials, structures and design.

6. DECISION PROCESS IN STRUCTURAL DESIGN

6.1 General Aspects

The term Decision Process suggests an analytical model with clearly defined gates as decision points. This is an important step beyond the preceding considerations regarding structural design. The implications of establishing such a model for the decision process in structural design will now be considered.

Many details on environmental and operational conditions are required for the model of a decision process. These details are different for each structural component -- where a component may be as complex as a fuselage shell or as elementary as a simple fitting. This means that a generally applicable model cannot be established. It is possible, however, to establish a general framework which can serve to clarify basic ideas and which can be expanded into the model for the decision process in the structural design of a specific component.

Decisions have to be made throughout the process of structural design. Even minor routine decisions, like edge distances, tolerances, etc., can assume major importance regarding airworthiness or cost. From an overall viewpoint, however, the decisions connected with the choice between various materials and design concepts are of dominant importance because of their pervasive influence. The corresponding responsibility of finding an optimum solution makes design several orders of magnitude more complex than analysis. At present, programs have been perfected for determining a minimum weight design of simple structures with multiple loading conditions and constraints on stress, displacement, and size of elements. Yet the decision process for an optimum design must also include cost, risk, and many technical characteristics. An optimization algorithm for design problems with a large number of variables has not been developed as yet.

Development of a model for the decision process in structural design includes the following aspects:

a. Overall analysis for strength and stiffness resulting in the sizing of structural elements -- a clearly recognized field which is being investigated systematically, with particular emphasis on computerization.

b. Analysis of design details giving full attention to the complexities of interaction between materials and structures -- a field of recognized importance which, however, due to its innate intricacies does not lend itself to a well-defined system.

c. Optimization with respect to weight, cost, risk, etc. -- a difficult field of increasing importance as new materials are introduced.

6.2 Screening, Selecting, and Detail Design

Any combination of material and structural configuration forms a design concept. Choosing between various design concepts requires a systematic approach because a multitude of considerations are involved and have to be examined up to a point when a design concept can be discarded as inferior compared to others.

A procedure proposed in Ref. 8 from the viewpoint of materials evaluation is just as well applicable to the more general subject of structural design. Three major stages can be distinguished:

a. Screening -- which is concerned with establishing a clear demarcation line between acceptable and non-acceptable so that many possibilities can be eliminated at the beginning;

b. Selecting -- which is concerned with trade-off studies between candidate materials and structural configurations, i.e., quantitative as well as qualitative considerations resulting in the basic decisions regarding structural design;

c. Detail Design -- which is concerned with establishing all the data required to permit the design and fabrication of a component which will function with a specified reliability.

A systematic approach along these lines is shown in Fig. 4 where each vertical stem represents a different design concept. The complexities which are inherent in comparing a large number of potential materials and configurations are substantially reduced because for each successive stage the number of possibilities is decreased while the depth of the investigation is increased.

The first stage, screening, includes many possibilities on a cursory level. It may suffice, for example, from the viewpoint of materials to check only for specific strength, specific modulus, fracture toughness, fabricability, and corrosion resistance; from the viewpoint of structures to check only for relative weight; and from the viewpoint of design to check only for relative cost. Such a brief but systematic screening process will eliminate many candidate design concepts.

The second stage, selecting, is the substance of advanced design. The design concepts which have survived after screening are considered on the much more thorough level which is required for trade-off studies, leading to the well-considered final selection of material and configuration.

The final stage, detail design, has to be based on full detail information. This may require expensive and time-consuming tests as well as other refinements which would not be justified for purposes of comparison.

Each stage of a design concept consists of several phases which can suitably coincide with those outlined in Fig. 3. It is seen that the decision process (Fig. 4) incorporates the design process (Fig. 3) and involves its repeated and selective application with full emphasis on trade-off considerations.

An analytical model of the decision process will be different for each type of component. Since many components are recurrent throughout aircraft design, the considerations regarding basic components (Section 4.7) are completely applicable. Systematic development of analytical models for the decision process for typical components is of basic importance. An important first step has been taken by the Air Force Flight Dynamics Laboratory with the initiation of a project to develop a model for analytical techniques of sizing the structural elements of a wing. This is in line with item "a" of Section 6.1.

6.3 Specific Aspects of Trade-off Considerations

Trade-off considerations have always served as means to the end of selecting a design concept. In earlier days the designer of less complex aircraft made his selection to a large extent intuitively. As complexities increased, this became obviously inadequate but no methodology has been developed yet. In spite of the growing number of materials and corresponding structural configurations which will soon be available, engineers have shown only a peripheral interest in this field.

At present, trade-offs consist of rather rudimentary considerations. The most fundamental parameters for trade-off considerations are cost, weight, time, and risk. Besides, there are qualitative considerations about technical characteristics which cannot easily be expressed in these terms.

Cost is a basic responsibility of design. Value engineers are the specialists in this field and some basic cost considerations are listed in Table 1. No basic difficulties exist in this field (except the usual cost overruns).

Structural weight is a basic responsibility of structures, and weight groups have done systematic work in this field for a long time. Weight can be related to cost when the value of weight saving has been established. This value, however, generally varies during the design process. Some basic considerations are summarized in Table 2. A plot for cost-weight effectiveness (Ref. 12) is shown in the figure at the bottom of Table 2. This allows for sloping lines to indicate various magnitudes for the value of weight saving and to compare different designs.

Risk is involved throughout aircraft design. It appears in each of Tables 1 to 3 and may be expressed as probability of occurrence, probability of success, or probability of survival. The question "what risk is involved?" must be asked throughout the process of structural design. Alternate possibilities and back-up solutions have to be evaluated. Risk is basically of a statistical nature -- but statistical data are mostly lacking in the introduction of new materials. Much of this uncertainty is contained in the general field of DDT&E (design, development, test, and evaluation). A breakdown requires detailed engineering forecasts which become meaningful only when they provide clear visibility for the underlying line of thinking. Regions of concern and of confidence have to be specified and analyzed.

Qualitative values refer to considerations which cannot easily be expressed in terms suitable for comparison. With some effort, many of them (e.g., fasteners, welding, heat treat and finish requirements) may be expressed in terms of cost-weight effectiveness. Others, like growth potential, remain evasive. Also to be included are individual judgment and experience which play a major role but acquire an acceptable significance only when they are broken down into discrete elements which are made visible and can be subjected to critical qualitative values which have to be quantified for comparison -- but no methodology exists in this field.

The preceding trade-off considerations range from clearly quantitative values like cost and weight to qualitative considerations about technical characteristics and to the uncertainties of risk evaluation. The latter two are characterized by general vagueness and there is much ambiguity in the interrelation between cost, weight, risk, and qualitative values. Yet trade-offs between these parameters are of basic importance. Any attempts to arrive at a decision process in structural design amount to self-illusion unless clear interrelations can be established.

Establishment of these interrelations can be expected to result eventually in objective functions for design optimization. Most work in this field is still limited to objective functions minimizing weight only while satisfying various constraints. More general considerations have to be based on concepts and procedures connected with advanced design as will be seen in the following discussion.

6.4 Outline for Decision Process in Structural Design

The preceding trade-off considerations contain a number of unsolved problems which will be discussed in Section 7. Holding them in abeyance, the outline of a decision process in structural design can be established in the following steps:

a. Since the analytical model for the decision process is different for each type of component, typical basic components have to be identified (Section 4.7).

b. For each basic component, design data are established to specify the given design conditions (Section 4.5).

c. The corresponding responsibilities for structural design are defined and assigned (Fig. 2).

d. This leads to the establishment of controlling parameters implicit in Fig. 3.

e. The procedures shown in Figures 3 and 4 and outlined in Sections 4.8 and 6.2 are combined.

f. Trade-off considerations are applied (Section 6.3).

g. Computerized methods for overall sizing are combined with weighed decisions in the fields of design details and optimization, providing for stepwise improvements in methodology.

7. DISCUSSION

7.1 Summarizing Basic Aspects

The present investigation is concerned with basic aspects of the decision process in structural design. It starts with a consideration of the increasingly important role which materials engineers and design engineers will have to play as new materials are introduced and develops a method of approach which is shown schematically in Figures 3 and 4 and summed up in Sections 4.8 and 6.2. The result is an outline for the decision process which is described in Section 6.4.

This outline is quite unsatisfactory with regard to details of an analytical model for the decision process. It is highly significant, however, with regard to recognizing the difficulties which have to be overcome before a meaningful analytical model can be established.

For the following discussion of principal aspects it may be helpful to look at structural design from a viewpoint expressed in Fig. 5. It shows the dual aspects of airworthiness and design optimization -- where the latter becomes increasingly important with the introduction of new materials.

Fig. 5 indicates that, at one end of the spectrum, overall analysis for airworthiness lends itself readily to computerization. It is concerned with the sizing of structural elements and is based on available analytical methods. At the other end of the spectrum, theoretical considerations for design optimization will not be ready for practical application in the near future. The magnitude of the task and of the effort concentrated in this direction is shown in References 13 and 14 which give a concise survey of the subject and include an extensive bibliography.

The remaining fields of design details in the airworthiness section and practical trade-off considerations in the optimization section of Fig. 5 compose a region of particular and immediate concern for the decision process. This is the critical region of intricate interaction between materials, structures, and design which forms the crucial part of the present investigation.

The dashed lines at the bottom of Fig. 5 indicate relationships which may be established in the more distant future. Developments will undoubtedly go in a direction where the interaction between materials, structures, and design can be expressed analytically similar to overall analysis and where automatic search techniques can be employed for finding an optimum solution.

7.2 Considering Design Optimization

Any future developments depend on much basic clarification still to be done. Only recently the first steps have been taken to provide visibility for trade-off considerations and for the line of reasoning in the decision-making process. This visibility is of fundamental importance not only to the aircraft industry but also to the procuring agency (Ref. 1, Section 7).

The common interest of manufacturer and customer indicates the need for a coordinated approach to this basic aspect of design optimization. A slightly different set of assumptions may result in very different trade-off considerations. Basic ground rules still have to be established in view of the prevailing vagueness discussed in Section 6.3.

Such an effort will have to take into account the practical experience accumulated in advanced design. Any theoretical approach which is not solidly anchored in these realities is of limited value only. A prime objective has to be the establishment of practical guidelines for trade-off considerations.

7.3 Considering Airworthiness

The state of the art in overall analysis for the sizing of structural elements is quite highly developed and continuously expanded in a systematic way. New developments quickly become public property in published form. Problems are of a clearly analytical nature in the traditional field of engineering, can be adapted to a computerized solution, and hold promise for a systematic solution in the foreseeable future.

In the field of design details, however, a much more primitive state of the art is revealed by many recent difficulties. Practical applications are ahead of theoretical understanding. Experience serves as a guide but much of it is kept as privileged information and published, at best, in the form of restricted company manuals. This aggravates a situation which is difficult in itself: to anticipate problems as the frontiers of technology are pushed forward.

A large part of the problem is due to the multitude of operational and environmental conditions where a systematic approach has to be based on maximum availability of information and eventually will lend itself to computerization. Another part of the problem which becomes particularly important for new materials or new design concepts is the ever-present danger of not recognizing a critical condition. When existing experience is limited, the best available talent must be brought to bear on many minute details. This requires a vivid exchange of opinions and full communication among specialists of various disciplines on a level which cannot be computerized.

Practical progress will consist of two aspects: First, selection of basic components with typical operational and environmental conditions and determination of corresponding analytical techniques for increased automation. This is the field of overall analysis for sizing of structural elements and important steps are being taken in this direction. Second, in the field of design details, the difficulties are vastly greater. As mentioned in the preceding paragraphs, they extend into an industry-wide problem of dispersing information which will become acute with the introduction of new materials. Beyond this, the combination of a large number of diverse inputs and factors of uncertainty calls for an outstanding application of closest man-computer relationship.

7.4 Combining Design Optimization and Airworthiness

Airworthiness is concerned with the interaction of materials and structures. Design optimization is concerned with the technique of the decision process which includes all aspects of design (as defined in Section 4.1). Both together form structural design which contains the full interaction of materials, structures, and design.

For a systematic approach to this interaction, the basic problems in the fields of optimization and airworthiness will have to be attacked first. In addition, the general procedure discussed in Section 4 can be used. This includes the need for establishing a separate model for each type of basic component and the concept of a triangle of structural design.

This triangle of structural design identifies the critical region of interaction between materials, structures, and design. It incorporates the field in which no computer programs exist at present. With the development of programs for partial aspects, the close man-computer relationship discussed at the end of Section 7.3 for interaction of materials and structures will be extended to include design optimization.

In addition to the basic problems regarding airworthiness and optimization, the following points may be listed:

a. In the field of materials, the main problem consists of providing full information on materials characteristics for a multitude of operational and environmental conditions. This requires

   guidelines for materials evaluation and testing techniques in coordination with materials research and development;

   identification of critical material parameters and environmental conditions for typical components;

collection, interpretation, storage, and dissemination of the vast amount of test data which are being published;

publication of data generated by government contracts;

exchange of proprietary data within the industry on a give-and-take basis;

coordination of development work to avoid time-consuming gaps and money-wasting overlaps;

definition of components which can be used for structural and flight testing for comparison of various materials and design concepts;

consideration of educational programs for materials engineers.

b. In the field of structures, the main problem consists of anticipating every possible mode of failure for any combination of operational and environmental conditions. This requires

combination of computerized overall analysis with full consideration for variations due to interaction between materials, structures, and design;

creation of a mechanism for iterative variations;

systematic evaluation of experimental data;

systematic use of experience;

exchange of information on a give-and-take basis;

write-up of recently solved problems in form of comprehensive case studies.

c. In the field of design, the main problem consists of finding an optimum design with full consideration of weight, cost, risk, and qualitative characteristics. A step-wise approach will have to start with an awareness of the theoretical difficulties and a recognition of the need for practical considerations. This requires

methodology for optimization;

guidelines for trade-off considerations;

quantification of qualitative data;

visibility and traceability for decision process;

presentation of non-quantitative data to procuring agency;

consideration of educational programs for design engineers.

7.5 Considering Uncertainties

Special consideration should be given to a particular aspect of risk evaluation. Ref. 2 mentions the dilemma of the structural engineer who has to use sound technical judgment during the early design stages while pressures of schedules and of "positive" thinking provide an atmosphere which is detrimental to the consideration of potential problems.

This is a classical application of the very pertinent ideas expressed in Ref. 15 about the role of uncertainties, pointing out that no engineering study is complete without an "uncertainty analysis". Uncertainties are often suppressed, intentionally or unintentionally, when the engineer wants to "sell" an idea or feels constrained by managerial policy or time schedule. This results in a loss of his credibility and has undoubtedly contributed to the very serious difficulties which have been experienced in the field of interaction between materials and structures.

The difficulties will be compounded with the introduction of new materials. This type of uncertainty analysis forms part of the risk evaluation for design optimization -- a field where much work still has to be done (Section 6.3). A related field is risk reduction which includes exchange of information, utilization of available experience, and case studies of practical problems which have been solved (Ref. 1, Section 8).

7.6 Considering a Practical Approach

The preceding considerations identify a good number of problems which are not of a typical scientific-technological nature. Most of them are in border regions of engineering which have been ill-defined and neglected and for which no clear responsibilities have been assigned. These problems have to be faced in order to establish a meaningful decision process for structural design. Progress toward their solution is a prerequisite for a successful introduction of new materials and, therefore, of basic importance.

Listing such problems remains a paper exercise unless it leads to a practical approach toward their solution. Magnitude and urgency of the problems justify an effort on an industry-wide basis in order to avoid scattered and unrelated attempts. Emphasis on isolated aspects is not as important as an overall approach. It appears that a meaningful consensus about the best course of action can be reached by a small group of engineers who are thoroughly familiar with advanced design and who represent materials, structures, and design as well as various companies. The basic objective must be to find a common approach toward problems which are clearly recognizable now and which will become increasingly complex as they are postponed.

A wide variety of opinions exists about these problems. Conformity of opinions is neither possible nor desirable but thorough discussion of well-considered thoughts is imperative. A course of action will have to be steered between recognizing the need for dissemination of basic information and allowing for the reluctance of human nature to divulge too much of a hard-gained experience.

The present investigation necessarily consists of subjective reasoning and there is no objective method available to judge its merit. Few of the ideas are original, most of them express and rearrange concepts which are found in the aircraft industry in varying degree. A main purpose is to serve as a catalyst and as a basis of discussion in a field where no systematic approach exists yet.

8. CONCLUSIONS

a. Structural design of high-performance aircraft is at the threshold of important advances as new materials will furnish lighter structures and new computer programs will allow more sophisticated structural analysis. Systematic work along these lines proceeds in the traditional fields of materials and structures.

b. Interaction between materials and structures, however, has many unexplored aspects and has been the cause of unsuspected failures with far-reaching consequences. The introduction of new materials must be expected to multiply these difficulties unless an approach to the design process can be found which improves the situation fundamentally.

c. The outline of such an approach is shown, emphasizing the importance of interaction between materials and structures, including design considerations, and of design optimization. It is based on the concept of a triangle of structural design to identify a trinity of responsibilities: materials engineers are responsible for materials evaluation and application; structures engineers are responsible for airworthiness at minimum structural weight; and design engineers are responsible for design concept, detail design, and design optimization.

d. The triangle of structural design is concerned with the complexities of interaction between materials, structures, and design. It is based on the recognition of our present inadequacy to solve this intricate interaction in a methodical way. Since many of the existing data are not available in a systematic form and since unforeseen parameters may be encountered, particularly with new materials, it is essential to provide for a flexible approach, to identify present shortcomings, and to allow for stepwise improvements. As a consequence, a new emphasis is given to the accumulated knowledge, experience, and judgment which can be utilized by closest personal contact and coordination between specialized disciplines and which must be expanded systematically. It is within this region of interaction where the inherent limitations of automated analysis and the promising possibilities of man-computer relationship converge.

e. Composite computer programs which combine various parts of structural analysis into a comprehensive system are the subject of wide-spread efforts. They will find increasing application but, in the near future, they can offer only a partial solution to

structural analysis. These composite computer programs refer to overall analysis and have to be supplemented by additional analysis, duly considering all the implications of item d.

f. In addition to airworthiness considerations, the introduction of new materials requires an additional set of decisions for design optimization. Some basic concepts on a rather elementary level of design philosophy have to be agreed upon first, leading to a somewhat empirical approach. Theoretical efforts in the fields of structural synthesis and design optimization are promising but are not expected to be applicable to the overall problem in the near future due to difficulties in mathematical programing.

g. The three preceding items, d, e, and f, refer to fundamental aspects of the design process. It appears, however, that only one of them -- computerized techniques for overall analysis -- is given general attention. A systematic approach to the other two items -- interaction between materials and structures and design optimization -- is the main object of concern for the present investigation.

h. Problem areas are identified in Section 7. Attention is directed toward fields which are of basic importance but have not been emphasized during the past. The majority of these problem areas involves interaction between different disciplines and demands widening horizons in engineering. This indicates practical problems which require practical approaches.

i. The problems are of sufficient complexity and diversity and form such interwoven aspects of an overall picture that uncorrelated efforts are bound to be ineffective. A practical approach should consist of a cooperative effort of engineers experienced in advanced design to face these problems.

j. The present time seems to be particularly favorable for such an undertaking. No major competition is taking place in aircraft design to interfere with a joint effort and the corresponding lull provides a healthy climate for a deliberate and thoroughgoing effort to prepare for the clearly visible needs of the near future.

k. A particularly important step could be accomplished in line with the recommendation in the following section.

9. RECOMMENDATION

It is recommended that the preceding conclusions be made the subject of further consideration on an industry-wide basis. This can be done most effectively by a small group of engineers who are thoroughly familiar with advanced design and who represent materials, structures, and design as well as various companies.

An overall perspective is provided by the realization that introduction of new materials and increasing computerization result in a basically new situation. A considerable number of viewpoints will have to be coordinated for a common effort which can lead to a clear course of action.

It appears that the initiative will have to come from the Government by encouraging and sponsoring this pilot project.

[illegible]

[illegible]

[illegible]

[illegible]

FIGURE I

AIRCRAFT DESIGN PROCESS

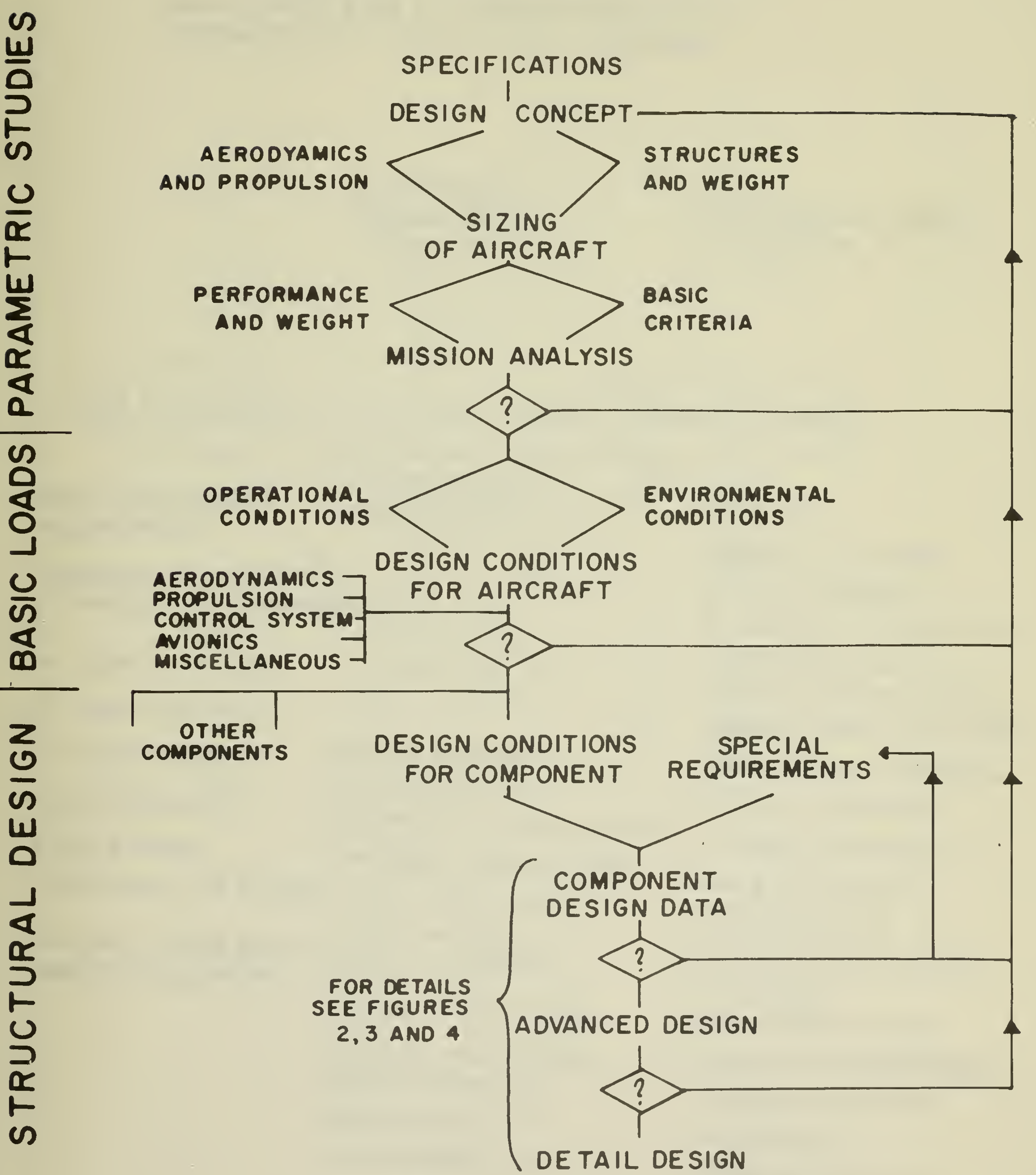
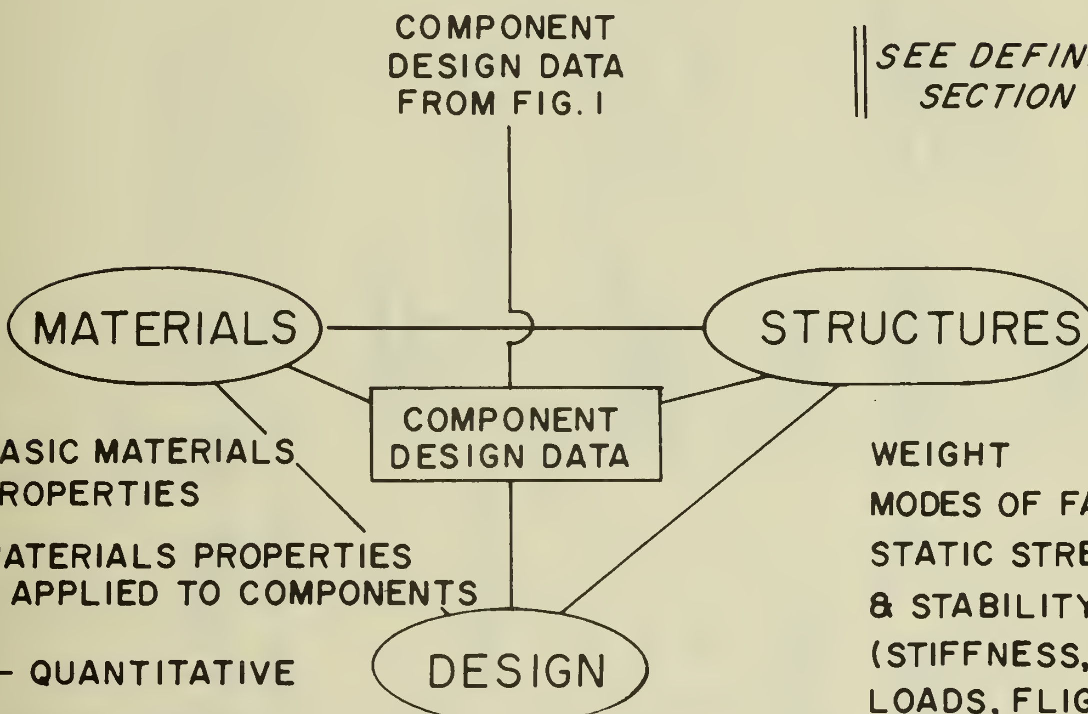


FIGURE 2

STRUCTURAL DESIGN PROCESS

BASIC PATTERN OF RESPONSIBILITIES
TRIANGLE OF STRUCTURAL DESIGN

SEE DEFINITIONS SECTION 4.1



MATERIALS

BASIC MATERIALS PROPERTIES

MATERIALS PROPERTIES APPLIED TO COMPONENTS
- QUANTITATIVE
- QUALITATIVE
- ENVIRONMENT

FABRICABILITY

PROCESSING

MATERIALS TESTING

PRODUCT RESEARCH AND DEVELOPMENT

DESIGN

DESIGN CONCEPT

DESIGN DETAILS

EQUIPMENT INSTALLATION

THERMAL PROTECTION

TIME SCHEDULE

COST-WEIGHT EFFECTIVENESS

OTHER TRADE-OFFS

GROWTH POTENTIAL

MAINTAINABILITY

REPAIRABILITY

VULNERABILITY

RELIABILITY

INSPECTION PROCEDURES

STRUCTURES

WEIGHT

MODES OF FAILURE

STATIC STRENGTH

& STABILITY; DYNAMICS (STIFFNESS, GUST, LOADS, FLIGHT LOADS, GROUND LOAD, FLUTTER, VIBRATIONS, CONTROL EFFECTIVENESS)

FATIGUE STRENGTH

RATE OF CRACK PROPAGATION

DAMAGE TOLERANCE

FAIL-SAFE CONSIDERATIONS

CREEP DEFORMATIONS

STRESS RUPTURE

ACOUSTICS

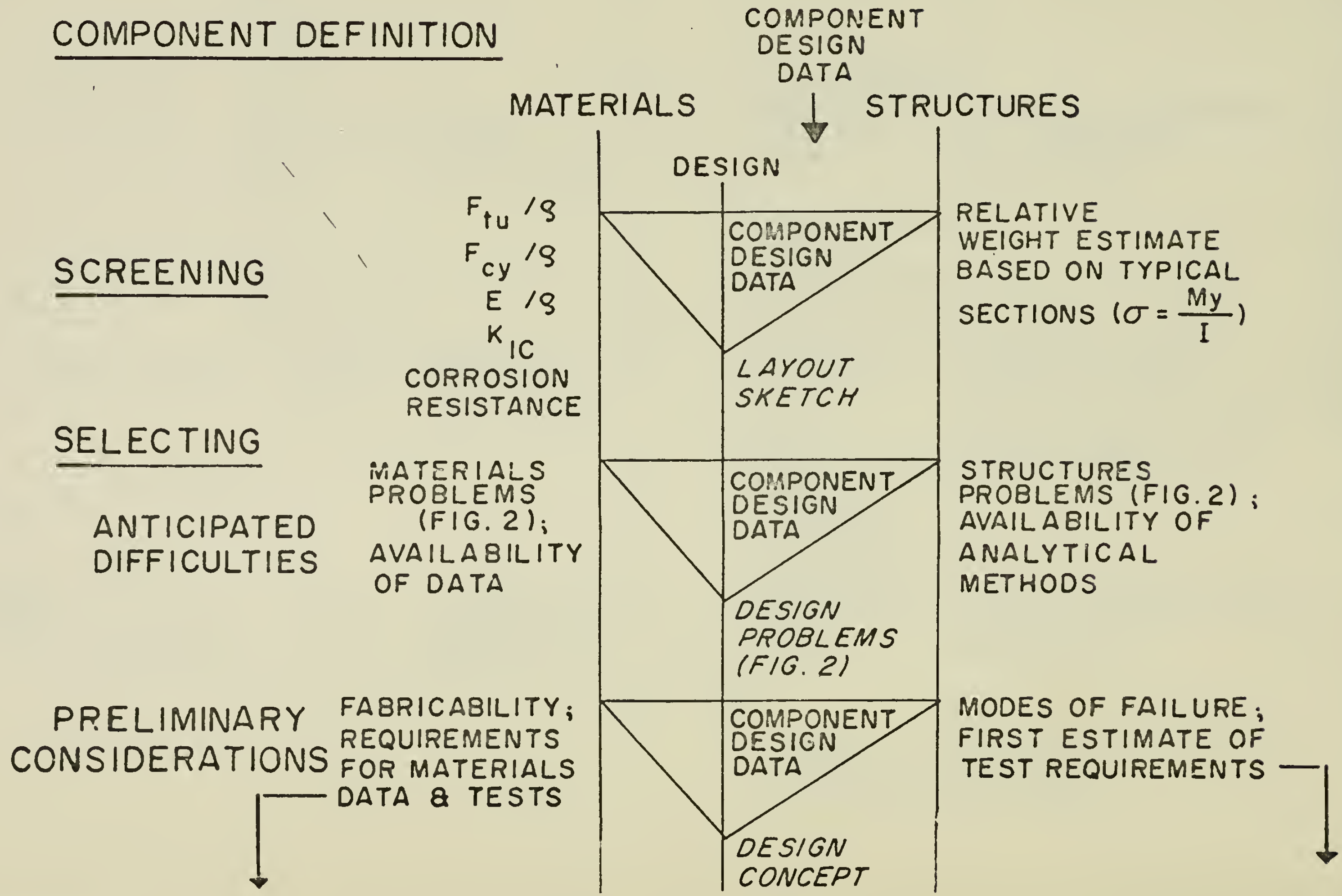
PROBABILITY OF SURVIVAL

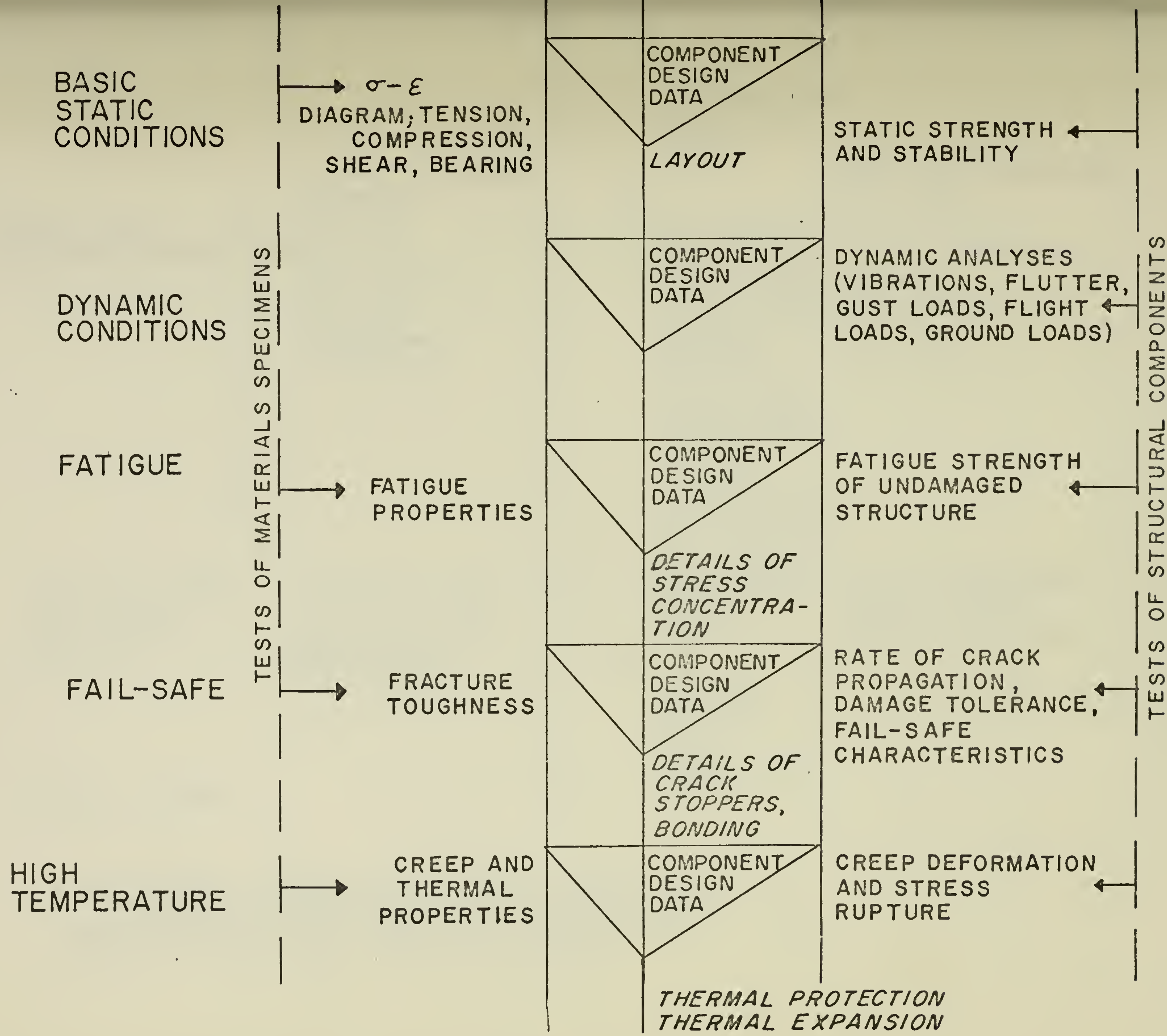
COMPONENT TESTING

FIGURE 3

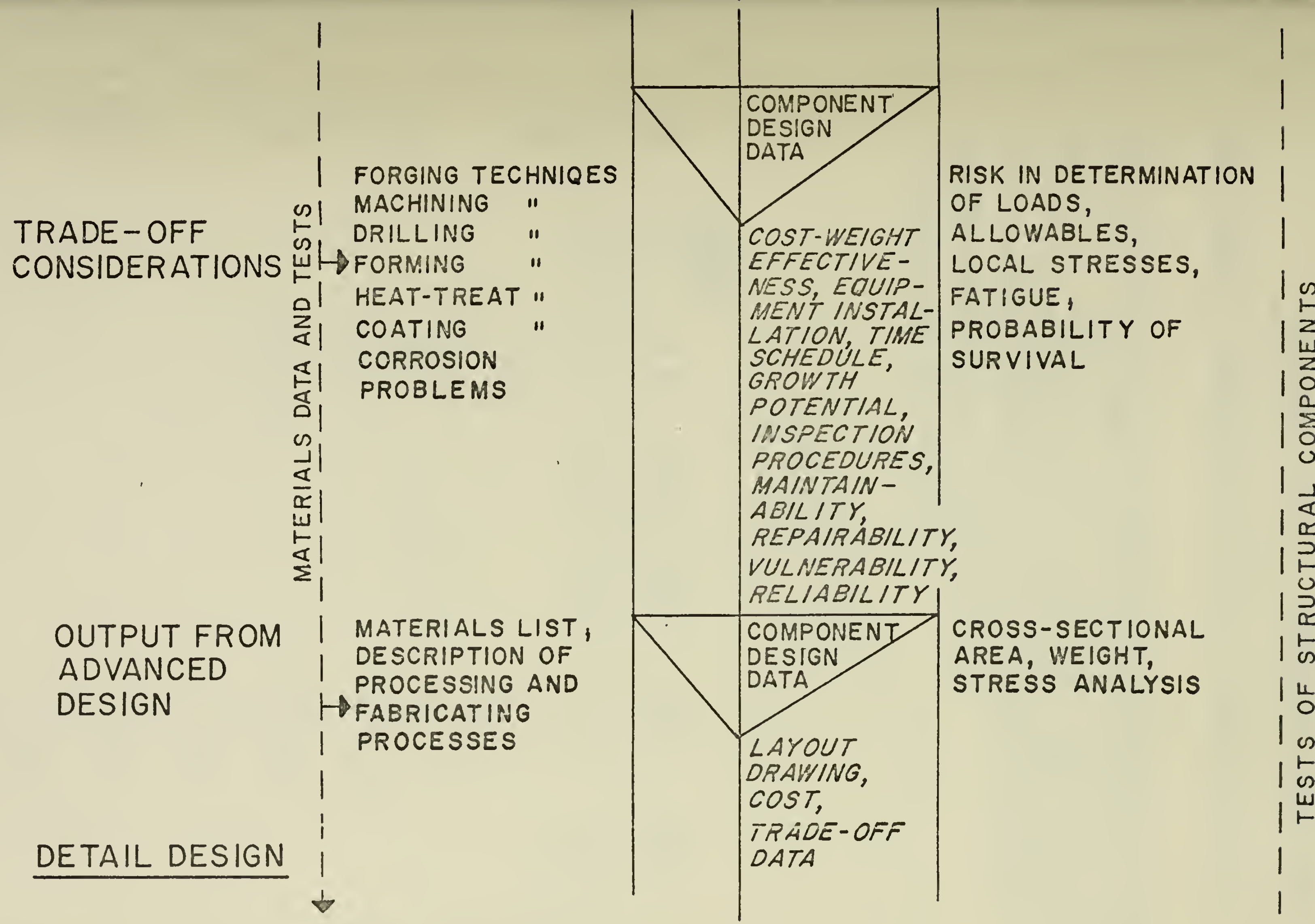
STRUCTURAL DESIGN PROCESS

EXAMPLE FOR DISTINCT PHASES





BASIC STATIC CONDITIONS
DYNAMIC CONDITIONS
FATIGUE
FAIL-SAFE
HIGH TEMPERATURE
TESTS OF MATERIALS SPECIMENS
σ-ε DIAGRAM; TENSION, COMPRESSION, SHEAR, BEARING
FATIGUE PROPERTIES
FRACTURE TOUGHNESS
CREEP AND THERMAL PROPERTIES
COMPONENT DESIGN DATA
LAYOUT
COMPONENT DESIGN DATA
COMPONENT DESIGN DATA
DETAILS OF STRESS CONCENTRATION
COMPONENT DESIGN DATA
DETAILS OF CRACK STOPPERS, BONDING
COMPONENT DESIGN DATA
THERMAL PROTECTION
THERMAL EXPANSION
STATIC STRENGTH AND STABILITY
DYNAMIC ANALYSES (VIBRATIONS, FLUTTER, GUST LOADS, FLIGHT LOADS, GROUND LOADS)
FATIGUE STRENGTH OF UNDAMAGED STRUCTURE
RATE OF CRACK PROPAGATION, DAMAGE TOLERANCE, FAIL-SAFE CHARACTERISTICS
CREEP DEFORMATION AND STRESS RUPTURE
TESTS OF STRUCTURAL COMPONENTS



THE PRECEDING PHASES ARE BASICALLY REPEATED — BUT REFINED FOR DOCUMENTATION OF AIRWORTHINESS AND MODIFIED FOR FINAL COMPONENT DESIGN DATA, MATERIAL PROPERTIES, AND TEST RESULTS.

FIGURE 4

STRUCTURAL DESIGN PROCESS

OUTLINE OF SCREENING, SELECTING, AND DETAIL DESIGN

THE VERTICAL STEM OF COMPONENT DESIGN DATA REMAINS ESSENTIALLY UNCHANGED. EACH COLUMN INDICATES A DIFFERENT CHOICE OF MATERIAL AND STRUCTURAL CONFIGURATION. EACH TRIANGLE OF STRUCTURAL DESIGN INCLUDES MATERIALS, STRUCTURES, & DESIGN. EACH SUCCESSIVE TRIANGLE INDICATES INCREASING DEPT OF INVESTIGATION.

FOR DETAILS SEE FIGURE 3.

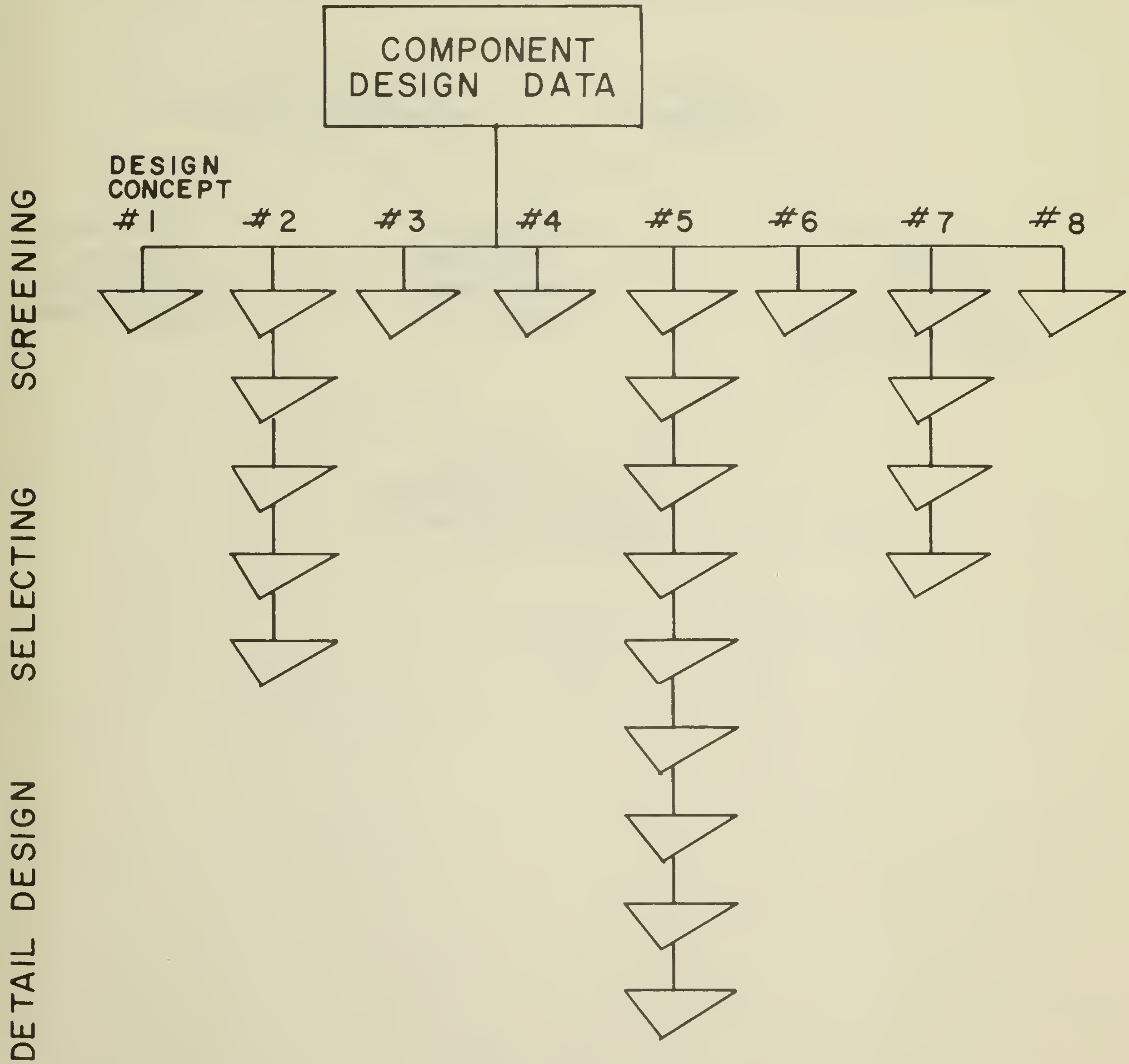


FIG. 5

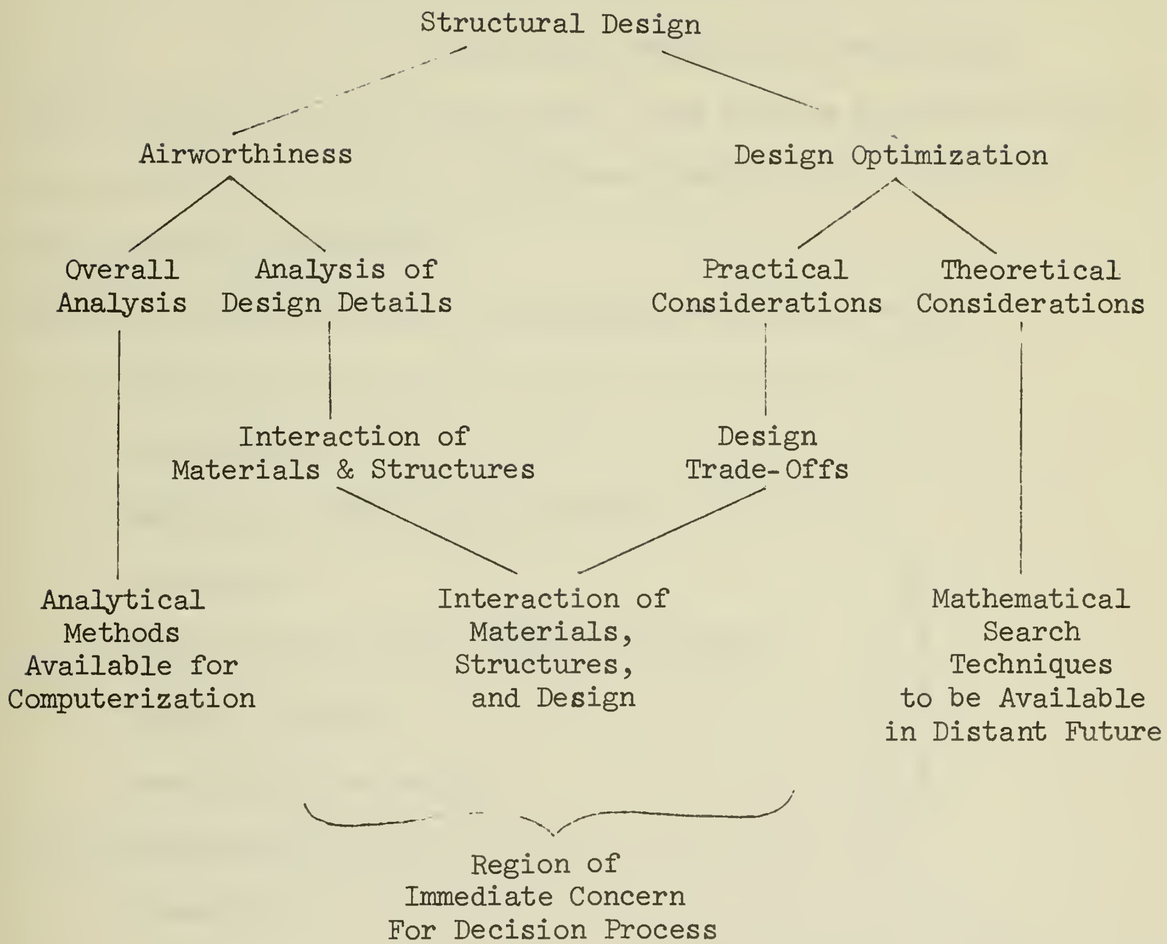

Structural Design
Airworthiness
Design Optimization
Overall Analysis
Analysis of Design Details
Practical Considerations
Theoretical Considerations
Interaction of Materials & Structures
Design Trade-Offs
Analytical Methods Available for Computerization
Interaction of Materials, Structures, and Design
Mathematical Search Techniques to be Available in Distant Future
Region of Immediate Concern For Decision Process

TABLE 1

COST CONSIDERATIONS IN STRUCTURAL DESIGN

Note: Either actual costs may be used or relative costs with respect to a base design.

Cost estimates for a new design have to be used in conjunction with risk evaluation. Any risk in new developments can be reduced by developmental expenditures.

Typical cost considerations influencing structural design:

1. DDT & E

2. Production

   Materials (incl. buy-fly ratio)

   Processing

   Manufacturing (incl. complexity factor)

   Quality control

   Quantity of production

3. Operation

   Inspection

   Maintenance

   Repair

   Spare parts

Risk evaluation

Technical Risk | Financial Risk | Time Risk | Substitute Solution

TABLE 2

WEIGHT CONSIDERATIONS IN STRUCTURAL DESIGN

Screening Process:	Weight estimates based on statistics, experience, and engineering judgment
Selection Process:	Weight computations based on design information

Weight

Airworthiness — Cost Effectiveness

Airworthiness → Structural Analysis → Probability of Survival; $\#/Ft^2$

Cost Effectiveness → Value Engineering → Probability of Success; $\$/Ft^2$

Cost-Weight Effectiveness

From Ref. 12

Indicated points refer to alternate design concepts

Value of weight saving determined by corresponding slope [$/#].

Cost of weight saving determined by slope of line connecting respective design concepts.

TABLE 3

TRADE-OFF CONSIDERATIONS IN STRUCTURAL DESIGN

Materials	Risk Evaluation
Availability of Information Available Experience Anticipated Difficulties in Materials Evaluation, Processing, Manufacturing, Maintenance Heat Treatment vs. Brittleness Fabricability Inspection Methods Reliability	Probability of Success
Structures	
Available Experience Availability of Analytical Methods Overall Analysis Analysis of Design Details	Probability of Structural Survival
Design	
DDT&E Availabel Experience Cost Considerations Cost-Weight Effectiveness Inspectability Equipment Accessibility Maintainability	Probability of Success
Repairability Reliability Vulnerability	Probability of Occurrence
Growth Potential Time Schedule Required Resources Alternate Solutions Cost of Failure	Red Flags !

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13. ABSTRACT

The decision process in structural design becomes increasingly important with the introduction of new materials. Starting from a consideration of present problems in structural design, an outline is developed for the decision process with particular emphasis on interaction between materials, structures, and design. This outline, however, still lacks the details which are required for an analytical model of the decision process. These missing details are identified and a practical approach toward their solution is shown.

14 KEY WORDS	LINK A		LINK B		LINK C	
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Structures						
Design						
Airframes						